1   **DEUTERIUM HEAT GENERATOR**

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4

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8

9 Cross-References:

10 Disclosures filed by the inventors at the Patent & Trademark Office, Washington D.C:

11   1. Disclosure Document Number 381513 dated August 31, 1995.

12   2. Disclosure Document Number 401865 dated June 28, 1996.

13 Other references:

14   4. "The Pathway to Commercial Applications", by J. L. Waisman and R. H.

15   Summerl, the Proceedings of the Seventh International Conference on Cold

16   Fusion, held in Vancouver, British Columbia, Canada, April 19-24, 1998, p

17   414.

18   5. Technical Note TN-7.1 "The Thermodynamic State of a Gas/Solid System"

19   issued by J. L. Waisman & R. H. Summerl, revised 9-20-99.

20   6. "The Emergence of a Coherent Explanation for Anomalies Observed in D/Pd

21   and H/Pd Systems: Evidence of ^{4}He and ^{3}He" by Michael McKubre, et al,

22   ICCF-8, March 2000.

23

24   **<u>Background of the Invention.</u>**

25   In the 1980's, Fleischmann and Pons (F&P) discovered that excess heat was

26 produced when electrolyzing heavy water using a palladium (Pd) cathode. Their

27 1989 announcement brought on a rash of hurried experiments by the technical

28 community to try to replicate the effect that had become known as "cold nuclear

29 fusion". Most such experiments failed; some for good cause. F&P sometimes had

30 trouble replicating their own work. Nuclear physicists denounced the cold fusion

31 effect because they believed that: (1) the same radiation products of deuterium fusion

32 that had been experienced in 'hot fusion' should have been detected and (2) the

33 Coulomb repulsion forces could be overcome only when temperatures in the

34 100,000,000°C range are produced. Cold fusion was branded as an incredible hoax

1 and virtually all funding in the United States was halted.

2   Throughout the 1990's, a number of dedicated scientists in laboratories around

3 the world continued the research. More and more were successful in producing

4 excess heat by electrolysis and some succeeded in measuring the helium products of

5 the reaction. The heat generation densities were low and the helium measured was

6 very small and did not show a consistent relationship with the timing and rate of heat

7 production. In all cases, investigators were pursuing the highest possible

8 concentrations of deuterium in the palladium lattice as the enabling process; the

9 highest concentrations being achieved at lower temperatures.

10   Some groups tried to achieve high D/Pd concentrations by gas loading but

11 were unable to reach the ultra-high gas pressures to equal the high equivalent

12 pressures achieved by electrolysis.

13   Other groups gave gas loading their best effort hoping to measure energized

14 particle radiation from the deuterized palladium and other hydrogen absorbing

15 metals. Again their efforts were spent in trying to achieve very high D/Pd

16 concentrations. Such experiments all failed for not recognizing that high temperature

17 is a key ingredient for enabling a fusion reaction by gas loading.

18   More recently, four successful experiments which produced excess heat and

19 showed the helium byproducts, that had been performed in four different laboratories,

20 were carefully replicated at SRI, Int. (See Reference 6.) This replication work

21 removes doubt about the reality of cold nuclear fusion which is now becoming known

22 as 'solid state fusion'.

23   But for one notable exception, all of the reaction rates were very low and of little

24 practical use. In their very early work, F&P actually produced high density heat,

25 accidentally at first and later in controlled experiments. This was their "boil dry" work

26 which they reported as "ignition" in the accidental case and "heat after death" in their

27 controlled boil dry experiments where the heavy water electrolyte was allowed to boil

28 away and the palladium cathodes became very hot for a long period of time. The data

29 from this boil dry work is shown on a plot of power density vs temperature in *Fig. 9* to

30 illustrate the significant effect of temperature in the production of high density heat.

31   It was this experimental work and other electrolytic work conducted at

32 somewhat elevated temperatures that captured the attention of the present inventors

33 who realized that the reaction rate was very much a function of temperature. The

34 higher heat densities at higher temperatures could easily be correlated to

1 thermodynamic principles but could not be correlated to higher D/Pd concentrations.

2 High D/Pd concentrations at elevated temperatures cannot be achieved as noted on

3 the equilibrium diagram for the deuterium-palladium system in *Fig. 8.*

4   The present inventors focused on the application of thermodynamic principles

5 that would cause one to look, at an elevated system-free-energy state, for a 'change of

6 state' of the deuterium within the confines of the metal lattice and that would enable

7 the fusion reaction; a change that nullifies the Coulomb repulsion forces and makes a

8 nuclear process possible. While this is a 'macro' point of view, it is now born out by

9 very credible 'micro' theories currently being developed by solid state physicists.

10   The present inventors also focused on the necessary requirements for there to

11 be commercial applications. For the cost of power production by this new method of

12 heat generation in palladium to be competitive with heat produced using fossil fuels, it

13 is necessary that it produce high density heat without the continuous input of power as

14 is required by the electrolytic methods. The present invention will produce heat

15 densities that are suitable for commercial applications at high temperatures without

16 the continuous use of power.

17

18   **Summary of the Invention**

19

20   The present invention is a reactor and system with a method for containing and

21 controlling a deuterium nuclear fusion reaction in a host metal lattice, such as

22 palladium, now generally referred to as 'solid state fusion'. The reactor is designed

23 for high temperature operation at moderate deuterium gas pressures and is operable

24 over a temperature range of 400°C to more than 1400°C. Temperatures up to 3000°C

25 are achievable for host metals with high melting temperatures.

26   The solid state fusion reaction is enabled and controlled by providing specific

27 combinations of reactor temperatures and deuterium gas pressures in the host metal's

28 surroundings. Free energy thermodynamic principles are applied to determine the

29 specific combination of temperatures and pressures for enabling and controlling the

30 fusion reaction. They involve providing a high system free energy state,

31 corresponding to a high deuterium-chemical-potential, that is above the threshold for

32 a 'change of state' of the dissolved deuterium where it can and will achieve a new

33 lower free energy. It is this 'change of state' that nullifies the Coulomb repulsion

34 forces and permits fusion to occur. (See the definition of chemical potential given

1 later.)

2   The deuterium, D, chemical potential is controlled by controlling the D gas

3 pressure, P, and the reactor temperature, T. **It must be remembered that for**

4 **every value of D chemical potential, there is a specific associated family**

5 **of temperature and D gas pressure combinations that will produce that**

6 **same chemical potential value** as is seen in *Fig. 7*. The fusion reaction is

7 accelerated by increasing the operating D chemical potential, above the threshold.

8   To provide metals capable of hosting the reaction, a selection process of

9 testing candidate host metals in a 'scanning reactor' is used to determine reaction

10 thresholds and heat rates. The measured threshold chemical potential establishes

11 the minimum operating conditions, temperature and pressure combinations, for the

12 onset of heat production for a particular host metal and form. The measured heat

13 production rates provide the temperature and pressure combinations necessary to

14 achieve a desired heat production rate.

15   A means for stabalizing the temperature of the reaction by controlling the heat

16 transfer rate is provided in the heat transfer system.

17   The reactor may be permanently sealed after 'loading' the deuterium, allowing

18 the reactor to be stored and later operated separate from its deuterium pressurizing

19 equipment. Use on a moving vehicle that requires portability of its energy source

20 would be a typical candidate application for the sealed reactor. An inert filler material

21 in the void space of the sealed reactor may be used to reduce the gas volume inside

22 the reactor thereby amplifying the pressure increase achieved with increasing

23 temperatures. For the amplification to be large, the void space volume must be

24 reduced to be on the same order as that of the palladium. The life of a sealed reactor

25 is limited due to the depletion of deuterium as helium is formed.

26   The heat-producing reaction is self-sustaining once enabled.

27

28   **Brief Description of the Drawings**

29

30   *Fig. 1* is a longitudinal cross-section of a typical reactor showing the general

31 arrangement of the host metal inside of the pressure vessel and the enabling heater

32 (coil) on the outside surrounded by the heat transfer surface. The configuration

33 shown in *Fig. 1* is typical for heat transfer by radiation where the outer surface has a

34 high emissivity. The enabling heater may be integrated into the heat transfer system if

1 desired, rather than in the heat transfer surface, as is illustrated in *Fig. 4* and in the

2 schematic in *Fig. 5*. *Fig. 1* also shows the location of the permanent seal when used,

3 the inert filler material when used, and the thermocouple when used.

4   *Fig. 2* shows the same typical reactor except with fins integrated into the heat

5 transfer surface for heat transfer by convection.

6   *Fig. 3* is a transverse cross-section of the reactor.

7   *Fig. 4* is an alternate arrangement where the host metal is located in a position

8 other than on the inside surface of the outer wall of the pressure vessel. Here the

9 enabling heat is provided by externally heating the heat transfer fluid during start-up.

10   *Fig. 5* is a typical schematic of the reactor and its operating system when the

11 heat transfer method is by forced convection. Alternate control systems may be

12 employed to suit the application requirements.

13   *Fig. 6* shows a general arrangement of the scanning reactor, the temperature

14 probe and a typical test sample.

15   *Fig. 7* is a plot of the 'System Free Energy State' versus 'Operating

16 Temperature' showing the range of operating chemical potentials, and the associated

17 temperatures and pressures, over which the present invention is operable. An

18 extended range is also noted.

19   *Fig. 8* is the Deuterium-Palladium TCP Equilibrium Diagram.

20   *Fig. 9* is a plot of selected experimental data showing where high density heat

21 was produced at high temperatures.

22

23   **Detailed Description of the Invention.**

24

25 **The reactor assembly**:

26   Referring to the *Fig's. 1, 2* and *3* the deuterium heat generator 1, is hereafter

27 called the 'reactor' or the 'reactor assembly'. The reactor assembly 1 consists of: the

28 pressure vessel 2; the host metal 3; the enabling heater 34; the heat transfer surfaces

29 4; a high pressure gas connector 5 to facilitate connection to the D gas pressure

30 manifold 13; a permanent sealing device 6 when used; an inert filler material 7 when

31 used; and a thermocouple 8 when used to determine the host metal temperature. The

32 heat transfer surfaces 4: may be plain; may have fins 35 for heat transfer by

33 convection; or may have a high emissivity coating for heat transfer by radiation. Heat

34 transfer by a combination of convection and radiation may also be employed when

1 that best suits the requirements of the application.

2   The reactor assembly 40 in *Fig. 4* illustrates how the host metal 3 may be

3 located in an alternate location in the pressure vessel. In this instance, the control

4 schematic (not shown) would embody the same principles that are embodied in the

5 schematic shown in *Fig. 5.*

6   When the reactor is to be permanently sealed, the opening to the reactor

7 assembly must include a suitable device 6 and method for sealing at its

8 predetermined 'loading' temperature and pressure. Such a device is one that

9 provides a slightly tapered hole in a thick walled, restricted section of the filler neck

10 that is transverse to the gas filling path and intersects it. An extrudable material is

11 held in the transverse tapered section to provide the 'working' seal. When the

12 permanent seal is to be made, the transversely held material is extruded into the filling

13 path using a side force. Both the side and end openings may then be electron beam

14 welded to form the long term permanent seal. Once the reactor is sealed, it must be

15 stored at a suitable temperature that is well below the threshold temperature to ensure

16 that the fusion reaction is not accidentally enabled. (See the later section on <u>How the</u>

17 <u>reactor works</u>.)

18

19 **The reactor body:**

20

21   In the preferred embodiment, the reactor pressure vessel body is made from a

22 suitable high-strength, high-temperature metal or alloy which has one or more of the

23 following properties: (1) impervious to hydrogen, (2) is not subject to hydrogen

24 embrittlement and/or (3) is coated on the inside with a material such as beryllium-

25 bronze which is impervious to hydrogen and its isotopes. The optimum diameter of

26 the reactor pressure vessel and the thickness of the material used to form the

27 pressure vessel body are determined by stress and strength analysis to suit the

28 operating conditions.

29   Generally, it is the application requirements that will set the design operating

30 temperature; the materials and dimensions for the reactor body must be appropriately

31 selected. In *Fig. 7*, the operable temperature range is from 400°C to more than

32 1400°C.

33   In the lower to mid-range operating temperatures of 400°C to 1000°C,

34 materials for the pressure vessel body may be selected from a group of alloys used in

1 the manufacture of jet engine turbine blades and in other high temperature uses. One
2 such material is Carpenter's Pyromet Alloy 680 which is ideal for the 400°C to 1000°C
3 range and is inexpensive and easy to machine.

4   For the higher temperatures in the 1000°C to 1400°C range, a material such as
5 pure tungsten may be used. The operating range shown in *Fig. 7* is applicable when
6 the host metal is a metal such as palladium with a melting temperature in the 1500°C
7 range.

8   When using tungsten for the reactor body, the operating range of temperatures
9 noted in *Fig. 7* may be extended up to 3000°C for use with a host metal having a high
10 melting temperature. Also, when using tungsten for the reactor body, the range of
11 operating deuterium chemical potentials may be extended into the 60kJ/mol range.

12

13 **The host metal:**

14

15   In the preferred embodiment, palladium is the host metal. Other candidate host
16 metals may be selected from a group consisting of: titanium, zirconium, vanadium,
17 thorium, lanthanum, praseodymium, tantalum, uranium, hafnium, nickel and cerium.
18 The host material may also be an alloy, or mixture, of the selected metal with one or
19 more other elements. Candidate host metal forms include wire, plate, foil, powdered
20 and deposited forms. The final selection of the host metals is described in a later
21 section, Host Metal Selection. The installation of the host metal is described in a later
22 section, Host Metal Installation.

23

24 **The reactant gas:**

25

26   In the preferred embodiment, the reactant gas is deuterium, D_2.

27

28 **How the reactor works:**

29

30   The objective of the method described in this section is to enable and
31 accelerate the heat producing reaction for the purpose of producing high density heat.
32 Using the reactor and system in this Specification and following this method will
33 create and exceed the system free energy states indicated by the experimental
34 evidence presented in *Fig. 9*.

1   The deuterium is dissolved in the host metal by virtue of its being in contact with
2   the surface of the palladium.   The concentration of deuterium in the palladium is
3   given by the D-Pd TCP Equilibrium Diagram as shown in *Fig. 8.*
4   At the high temperatures where the system is operative and high density heat
5   is being produced, *Fig. 9,* the D/Pd concentrations will be low as indicated on the
6   Equilibrium Diagram. There is no finite minimum D/Pd concentration required for
7   operation; only that some deuterium be present.
8   The heat producing reaction is enabled by raising the system free energy state,
9   corresponding to the deuterium gas chemical potential, to its reactive threshold level.
10   At the threshold level, the 'dissolved' deuterium undergoes a change of state, seeking
11   its lowest possible free energy. It is this change of state that nullifies the Coulomb
12   repulsion forces and enables the fusion reaction. The chemical potential of the
13   'dissolved' deuterium, at equilibrium, is uniform throughout the host metal and it is a
14   function of the deuterium 'gas' chemical potential at the surface of the host metal.
15   **The 'gas' chemical potential can be measured and controlled by**
16   **controlling the D gas pressure and the reactor temperature.** The threshold
17   of the heat producing reaction is the deuterium 'gas' chemical potential that produces
18   the 'dissolved' deuterium chemical potential that is critical to its change of state.   The
19   relationship between the gas chemical potential and the chemical potential of the
20   dissolved deuterium is explained in Technical Note TN-7.1, Reference 5, and is
21   shown explicitly in equations (h), (i) and (j) of that reference. The heat-producing
22   reaction is spontaneous once it is enabled. The rate of the heat production is
23   increased as the operating chemical potential is raised above the threshold.
24   For the sealed reactor, only the temperature can be controlled directly and the
25   pressure for any given temperature is a function of that temperature. The pressure
26   and the associated D chemical potential may be predicted for any given temperature
27   knowing the ratio of the 'free-gas-volume' to the 'palladium volume' installed in the
28   reactor as described in the later section, Predicting the performance of sealed
29   reactors.
30
31   **Chemical potential:**
32
33   In the present invention, the term 'D chemical potential' is used as a measure of
34   the free energy state of the system. The term 'chemical potential', when used for a

1 gas-metal system, is defined as the change in Gibbs Free Energy, in Joules per mol,
2 that would be required to force one more mol of a gas into a large gas/metal system,
3 at its present free energy state, while holding the temperature, pressure and the
4 concentration of other species constant. The chemical potential, μ, of the deuterium
5 gas is given by the equation:

6 $$\mu = (0.5RT)Log_n(P/P_0) \qquad \text{(Equation 1)}$$

7 where: μ is the gas chemical potential (J/mol), R is the gas constant (8.32
8 Joules/mol°K), T is the temperature in Kelvin, P is the deuterium gas pressure in
9 atmospheres and P_0 is the selected standard state pressure of 1 atmosphere. Since
10 the chemical potential of the dissolved deuterium is a function of the D gas chemical
11 potential, it is also a function of the two control variables, T and P.
12

13 **Host metal selection:**

14

15   The threshold deuterium gas chemical potential may vary from one candidate
16 host material lot to another. The threshold D chemical potential for a specific host
17 metal is also dependent on the system's electronic Fermi energy as well as other
18 factors including the purity, crystal size and regularity, and the population of flaws,
19 cracks, vacancies, distortions and dislocations in the crystal lattice structure of a
20 particular host material. Some of these micro-properties might be altered in the
21 process of installing the host inside of the reactor.
22   Because of this variation in micro-properties, each lot of the candidate metals is
23 subjected to screening tests, in their final form, to determine their threshold deuterium
24 gas chemical potentials. Such screening tests are conducted for any candidate host
25 metal in a properly instrumented pressure vessel. The material-form combinations
26 with the lowest threshold chemical potentials are the best candidates. The final
27 selection of a metal/form will be dictated by the application requirements.
28   The 'instrumented' pressure vessel for screening the candidate host materials
29 is called a 'scanning' reactor with means for temperature and deuterium gas pressure
30 control. For the scanning reactor to be an effective tool for the process of selecting the
31 host metal and form, it is designed for a broad operating range in terms of high D
32 chemical potentials, high temperatures and high pressures. When the reactor body is
33 made from pure tungsten, D chemical potentials up to the range of kJ/mol70,
34

1 operating temperatures up to about 3000°C and D gas pressures up to the range of

2 4000 atmospheres can be achieved.

3   A typical general arrangement of the scanning reactor and typical test samples

4 are shown in *Fig. 6.*

5   • The scanning reactor body 41 is designed to minimize heat conduction to its

6   attachment base and to minimize heat radiation to its surroundings. By

7   operating in the vacuum provided by the vacuum chamber 44, the losses

8   by convection are eliminated. The sensitivity of threshold measurements

9   and the accuracy of heat rate measurements·depend on how well the

10   reactor is isolated. The material for fabrication of the reactor body 41

11   should be selected from the group of candidates for the production reactor

12   noted in the previous section, The reactor body.

13   • The heater coil 42 is the means to control the temperature of the test sample.

14   • The base of the vacuum chamber 44 incorporates the D_2 gas pipe

15   connections 46 for the scanning reactor and the external piping. The base

16   also incorporates the electric wire feed-thru 45 and the vacuum port 48.

17   • The cross fitting 47 permits ready through access to the reactor body for the

18   test sample assembly 55 facilitating rapid change of test samples with just

19   a single high pressure disconnect. It 47 also provides side ports for the

20   high pressure D_2 gas from the gas supply system 51 and access to the

21   vacuum system 52. The D_2 gas pressure gage 50 provides the necessary

22   pressure data for calculating chemical potentials.

23   • The test sample assembly 55 consists of a substrate 56 and the host metal

24   sample 57. The host metal sample 57 is processed onto the substrate

25   using the installation process planned for the production reactor.

26   • The thermocouple 43 is the reference measurement for detection of the onset

27   of fusion heating by the thermocouple 54 on the temperature probe 53.

28   When the system is at thermal equilibrium and the fusion reaction is not

29   yet enabled, the two thermocouples 43 and 54 will read alike. When the

30   onset of the fusion reaction is reached, the thermocouple 54 on the probe

31   will read higher than than the thermocouple 43 on the reactor body. The

32   temperature rise (54 minus 43) due to the onset of 'fusion' heating is one

33   that persists beyond the transient heats due to dissociation, ionization,

34   solution and lattice transformation.

1   Measurement of the threshold D chemical potential is accomplished by
2 recording the reactor body temperature 43 and gas pressure 50 at the onset of the
3 heat producing reaction when a temperature rise 53 of the test sample above the
4 surroundings is detected. The threshold chemical potential is then calculated from the
5 Equation 1 noted above using that temperature 43 and pressure 50 recorded at the
6 onset.
7   Once the threshold D chemical potential is measured for particular sample,
8 there is a family of temperature and pressure combinations that will produce that
9 same D chemical potential. These data are a part of the temperature and pressure
10 conditions needed for reactor design.
11   The scanning reactor is also used to measure the heat production rates over
12 the range of operating temperatures specified for the application. For the scanning
13 reactor to be effective for measuring rates, it must also incorporate calorimetry. One
14 direct measurement method is by noting the reduction of control heater 42 power to
15 maintain constant temperature 43 when the test sample 57 is producing heat. For this
16 method of calorimetry, all heat losses must be minimized. To make these rate
17 measurements, the installed volume of the host metal sample 57 is adjusted so that
18 the heat generated at the test operating conditions is approximately equal to the mid-
19 range of heat produced by the heater 42. Knowing the heat necessary to make up the
20 losses in the system at the test temperature, the heater power may be reduced from its
21 'loss maintenance' rate to compensate for the heat generated by the test sample,
22 thereby maintaining a constant temperature and giving a direct reading of the heat
23 generated.
24   Knowing the volume or weight of host metal in the test sample, the average
25 power density may be readily calculated, in watts per cubic centimeter, for each level
26 of operating chemical potential applied. It is this heat production rate characteristic of
27 the host metal that will permit determination of the thickness of the host metal to be
28 used for a particular application.
29   The scanning reactor is also used to determine the slope of the heat generation
30 rate curve at the design operating temperature so that the heat transfer system may be
31 designed for stability. The slope of the heat transfer characteristic curve at the
32 operating conditions must be greater than the slope of the power production curve at
33 that point for there to be a stable operating temperature. Determining the slope of the
34 sample's characteristic heat production curve is accomplished by measuring the heat

1 generation rate over a range of temperatures above and below the design operating

2 temperature and plotting the data for analysis.

3

4 **Host metal installation:**

5

6   In the preferred embodiment, the host metal is affixed to the inside surface of

7 the reactor so that heat flow from the host metal to the heat transfer surfaces is

8 enhanced. Other designs may place the host metal at other locations inside the

9 reactor. This is illustrated in Figure 4 where the heat transfer surface is along the

10 central heat transfer fluid tube 36.

11   Candidate methods for installation of the host metal include: (1) various

12 deposition processes, (2) other solid forms, which may be on a substrate, and (3)

13 powdered forms sintered in place, or otherwise confined. Some candidate methods

14 of installing the host metal are briefly described here:

15   (1) Fabricate the host metal in the form of a tube in the metal-producing mill by

16   standard techniques of casting, and a series of "drawing" steps with

17   intermediate anneals. This is a "bulk" technique. The dimensions of the

18   host metal tube are such that the outside is a close fit to the inside of the

19   reactor body. The outside surface of the host metal tube may be coated

20   with brazing material. After insertion, a mandril may be inserted to

21   expand the host tube to an "interference" fit. The assembly is then

22   heated to the brazing temperature to produce a strong and conductive

23   interface.

24   (2) Another method employs the use of host metal in a powdered form,

25   available commercially, which is placed into position so the powder

26   tightly fills a tubular space inside the pressure vessel, kept in place by a

27   mandril. The assembly is then heated to the sintering temperature,

28   which produces inter-diffusion of host metal powder particles so they

29   become firmly attached to each other and to the inside surface of the

30   reactor body. The mandrel is then removed.

31   (3) Still another method is to use a vapor-deposition technique in which a

32   vapor of host metal is produced in an evacuated space and is deposited

33   in a layer on the inside surface of the reactor body.

34   The host metal is cleaned after installation to remove surface contamination

1 and facilitate the solution of deuterium.

2   The design thickness of the host metal will vary from a fraction of a millimeter to
3 several millimeters depending upon the host material selected, its measured heat
4 production rates over the operating temperature range and the required surface
5 power density, or heat flux, specified for the application.

6   The present invention is operable with any one of many installation methods.
7 In each case, the threshold D chemical potential and the power production
8 characteristics are determined by 'scanning' tests for the specific combination of host
9 metal and installation process to complete the design.

10

System control.

12

13   Heat production rate stability is preserved by maintaining a constant host metal
14 temperature for a given deuterium gas pressure. This is accomplished by ensuring
15 that the heat transfer rate away from the reactor is equal to the heat generation rate at
16 the desired operating temperature. Since the reaction heat rate is an exponential
17 function of temperature, positive temperature feedback and 'run-away' may occur if
18 the heat transfer rate is inadequate.

19   When heat transfer is by forced convection, the host temperature, for a given
20 deuterium gas pressure, is controlled by controlling the temperature and the flow rate
21 of the heat transfer fluid as seen in Fig. 5.

22   When heat transfer is by radiation, with a high operating temperature for the
23 reactor and a low receiver temperature, the heat transfer rate is essentially a fourth
24 power function of absolute temperature of the reactor. In general, if the reactor's
25 operating heat generating rate is less than a fourth power function of temperature,
26 then the reactor will be stable at the design operating temperature. If the heat
27 generation rate is greater than a fourth power function of absolute temperature, then
28 supplemental convection or conduction cooling of the reactor may be required to
29 maintain stability.

30

Control of the sealed reactor.

32

33   Startup and control of the sealed reactor is accomplished by controlling only
34 the temperature of the reactor.

1   The performance of a sealed reactor is determined the same way as that for a
2 pressure controlled reactor; the fusion reaction is enabled by producing the threshold
3 chemical potential measured for the host metal in the scanning reactor. The rate of
4 the reaction is increased by increasing the operating D chemical potential over the
5 threshold. The difference for the sealed reactor is that the internal D gas pressure
6 cannot be changed independently or even measured easily. It can, however, be
7 predicted and the D chemical potentials can then be calculated for any given
8 temperature.
9   By predicting the internal pressures and calculating D chemical potentials over
10 the operating temperature range, the threshold temperature and the heat generation
11 rates of the reactor at various temperatures above the threshold can be calculated.
12
13 **Predicting the performance of sealed reactors:**
14
15   When the reactor is operating in the sealed condition, the internal reactor gas
16 pressure, at any given temperature, is dependent on (1) the mass of the deuterium in
17 the host metal and in the void volume at the time of sealing, and (2) the ratio of the
18 'void-volume' to the 'host-metal-volume' inside the reactor. The pressure then is a
19 function of the reactor temperature and changes as the temperature changes.
20   To predict the pressure for any given temperature, it is necessary to first
21 determine the total number of mols of deuterium that were 'installed' at the time of
22 sealing. To determine the number of mols of deuterium in the host metal, the total
23 number of mols of host metal installed inside the reactor must be known and the
24 reactor temperature and gas pressure at the time of sealing must have been
25 measured. The number of mols of dissolved deuterium within the host metal is then
26 determined using concentration data from the TCP Equilibrium Diagram, Figure 8.
27 The number of mols of deuterium in the void volume, n, is calculated using the ideal
28 gas law, $PV=nRT$. The sum of the two numbers is the total installed deuterium and it
29 will remain the same at any other temperature once the reactor is sealed.
30   As temperature is increased, some of the dissolved deuterium in the metal will
31 be driven into the void volume thereby amplifying the pressure increase that would
32 have occurred had there been no change in the concentration of deuterium in the host
33 metal. At the higher temperature and at the resulting higher pressure, a new
34 equilibrium will be reached which will further increase the operating D chemical

1 potential and hence the reaction rate. The pressure amplification factor is a function
2 of the ratio of 'void-volume' to 'host-metal-volume'. This ratio may be adjusted in
3 design by adding an inert filler material to fill the void space.

4 When the void volume is large relative to the host-metal volume, the pressure
5 amplification due to deuterium expulsion from the host metal with a rise in
6 temperature is small. When an inert filler material is used to significantly reduce the
7 void volume, the pressure amplification as a result of deuterium expulsion from the
8 host metal may be made very large (in the range of 100 times and more) depending
9 on how much the void volume is reduced by the filler. The preferred material for the
10 inert filler material is one which is relatively impervious to hydrogen. The filler
11 material may be a solid core or a closely packed loose material. Quartz or alumina
12 are candidates for the filler material.

13

14 **Useful life of the sealed reactor:**

15

16 The useful life of the reactor, when operating sealed, is limited since deuterium
17 is depleted in the reaction. As deuterium is converted to helium, the partial pressure
18 of the deuterium in the void space will decrease and the partial pressure of the helium
19 will increase. This decrease in the partial pressure of the deuterium will have the
20 effect of reducing the operating D chemical potential and hence the rate of the fusion
21 reaction.

22 When the application requires that the heat generation rate remain constant,
23 then it will be necessary to compensate for the drop in pressure by operating the
24 reactor at a correspondingly higher temperature to maintain the same operating D
25 chemical potential. In convective heat transfer, this is accomplished by decreasing
26 the heat transfer rate. This action will cause the temperature to rise and the correct
27 operating D chemical potential to be restored. When the operating heat generation
28 rate is restored at a higher temperature, then the heat transfer rate may require
29 readjustment so that it is equal to the restored heat production rate.

30 In this case, the useful life of the sealed reactor is limited to how much
31 adjustment in operating temperature can be made before the maximum temperature
32 allowable for that particular reactor body design and material is reached.

33 When the application can tolerate a drop in the heat generation rate, then the
34 useful life of the sealed reactor is limited to the time to reach the minimum heat

1 generation rate that meets the minimum application requirements.

2

3 **The Operating System:**

4

5   A given reactor operating system is designed to fit the application requirements
6 in terms of the operating conditions and the method of heat transfer. As a minimum,
7 the control system must incorporate: (1) a means to load the deuterium into the reactor
8 and host metal, (2) a means of controlling the chemical potential of the dissolved
9 deuterium, (3) a means of extracting all of the generated heat and thereby providing a
10 means of controlling the temperature of the host metal.

11

12 **Loading the Reactor:**

13

14   Referring to *Fig. 5,* the deuterium gas pressurization system consists of a gas
15 storage system 9, pressurization pumps 10, vacuum pumps 11, isolation valves 12, a
16 high pressure manifold 13 to interconnect the components and to connect the system
17 to the reactor assembly 1. The pressure in the manifold is indicated by pressure gage
18 14 which may include an electronic pressure signal to the operating control panel 27.
19 The gas storage system 9 may include filters, traps, regulators, etc.
20   The reactor 1, the manifold 13, the pressurizing equipment 10, the gas storage
21 equipment 9 and associated lines are evacuated through the isolation valves 12
22 using the vacuum pumps 11 to remove contaminating gases. When the enabling
23 heater 34 (in *Fig. 1 & 2*) is not integrated into the heat transfer surfaces, then the
24 operating chamber 15 heater 17 may be operated to raise the temperature of the
25 reactor to a value in the 600 to 800°C range for an extended period of time while
26 under vacuum to remove residual contamination from the reactor and host metal.

27

28 **Typical loading procedures:**

29

30   In the preferred loading method, the temperature of the reactor 1 and the
31 operating chamber 15 is raised above 400°C while still under vacuum using the
32 enabling heater 34 (*Fig. 1 & 2*) or heater 17 (*Fig. 5*). The heat transfer fluid pump 20 is
33 off during the loading procedure. The isolation valves 12 are closed and the
34 deuterium gas supply valve and regulator 9 are opened. The deuterium gas is

1 pumped into the high pressure manifold 13 and reactor 1 using the pressurization

2 equipment 10 controlled from the control panel 27 and is indicated on the manifold

3 pressure gage 14. The gas pressure is raised to that value necessary, at the loading

4 temperature 8, to achieve the threshold chemical potential for heat generation and the

5 reactor 1 is ready for operation as a heat generator. When the threshold chemical

6 potential cannot be reached at the selected loading temperature, then a higher

7 loading temperature must be used. An alternative is to load at the lower temperature

8 and then raise the temperature until the threshold is reached.

9   When the reactor is to be used as a sealed reactor, it is loaded with deuterium

10 to a predetermined temperature and pressure and then sealed. The final loading

11 temperature and pressure at sealing are selected so that the deuterium gas pressure

12 inside the reactor will reach the correct pressure at the design operating temperature

13 to produce the required D chemical potential which, in turn, produces the desired heat

14 generating rate.

15   After permanently sealing a reactor, it may be removed from the pressurization

16 system and stored for later use as a heat generator. Controlled low temperature

17 storage may be required to ensure that the threshold chemical potential is not

18 accidentally reached.

19

20 **System operation:**

21

22   Referring to *Fig. 5*, the operating chamber 15 consists of: insulation 16 on the

23 outside, a heater 17 on the inside (or other means of heating the reactor for start-up),

24 a heat transfer fluid distribution system 18 which ensures that virtually all of the fluid

25 impinges on the reactor's heat transfer surfaces, an inlet temperature thermocouple

26 28 for control of the fluid temperature as it begins circulation over the reactor surfaces.

27 A calorimetry system 30 utilizes inlet and outlet thermocouples 32 & 33 and the heat

28 transfer fluid mass flow meter 31 to determine the heat generation rate.

29   The heat transfer system utilizes a heat transfer fluid, circulating in lines 19, 23

30 and 25, which may be a gas or a liquid to suit the application, and consists of: the

31 circulation pump 20, mixing valve 22 for controlling the temperature of the heat

32 transfer fluid 28 at the inlet of the operating chamber 15, the cooling heat exchanger

33 24 and cooling line 25 which supplies cooler fluid to the mixing valve 22, a heating

34 by-pass line 23 which provides hotter fluid to the mixing valve 22, flow rate control

1 valve 26 to provide heat production stability control by ensuring that the heat
2 transferred out is equal to the heat generated in the reactor, and the mass flow meter
3 31 which provides data required for calorimetry 30. The loads 21 and heat rejection
4 devices 24 remove the generated heat. The flow rate control valve 26 may be
5 eliminated if the pump 20 has a flow-rate control feature built into the pump.
6   Before operating the system, the operating chamber 15 and all of the heat
7 transfer fluid components, including the heat-using devices 21, are purged of all
8 unwanted fluids and the selected heat transfer fluid with a known specific heat is
9 introduced.
10

Typical Operation at the Desired Power Production Rate

12

13   Once (1) the reactor 1 and the heat transfer system have been brought up to
14 the design operating temperature range 8, (2) the deuterium gas pressure 14 has
15 been increased so that the threshold of heat production has been surpassed and (3)
16 the reactor heat generation rate exceeds the system loss rate, the heater 17 (or the
17 enabling heater 34) may be turned off. The host metal temperature is now under
18 control of the heat transfer system. It is controlled by adjusting (1) the mixing valve 22
19 position to provide heating 23 or cooling 24 & 25 of the heat transfer fluid after heat is
20 extracted by the loads, and (2) the heat transfer fluid flow rate control valve 26.
21   The average power production rate is controlled by controlling the reactor
22 temperature 8, as noted above, and the deuterium gas pressure 14 so that load
23 demands 21 are met with the mixing valve 22 in approximately the center position.
24 Short-term changes in load demand are met by adjustments in the heat transfer fluid
25 temperature 28 and flow rate 26. Reactor stability control takes priority over load
26 demand.
27   When the reactor is operating sealed, the heat generation rate is modulated by
28 adjusting the operating temperature 8. As the deuterium is depleted, the power
29 production rate for a given temperature will decrease. To compensate, the reactor is
30 operated at gradually higher temperatures over the life of the reactor. This is
31 accomplished by adjusting the flow rate control vale 26. A reduced flow will increase
32 the operating temperature and an increased flow will reduce the operating
33 temperature. After any adjustments in temperature, it is necessary to restore the heat
34 transfer rate to be equal to the generation rate for stability.

1   With the reactor is operating unsealed, it, and its operating system will require
2 periodic maintenance to remove the product of the reaction, helium. When the reactor
3 is operating sealed, it will require periodic recycling to remove the products of the
4 reaction.

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